Aspects of Sensor Networks

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SET-157

Multisensor Fusion:
Advanced Methodologies and
Applications

Outline

- Synchronization
- Coverage
- Localization
- Ambiguity function
- PDOP - Position Dilution Of Precision

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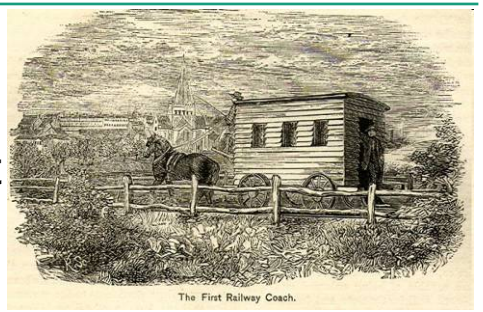
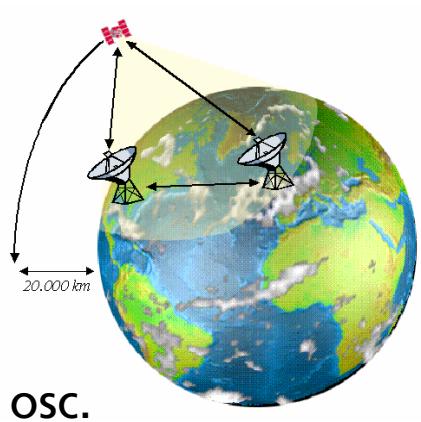
Synchronisation
- historical notes -

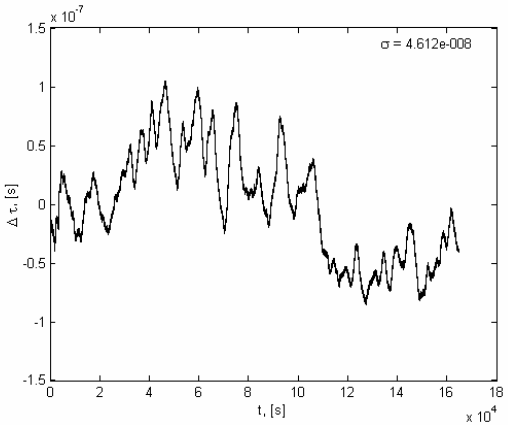


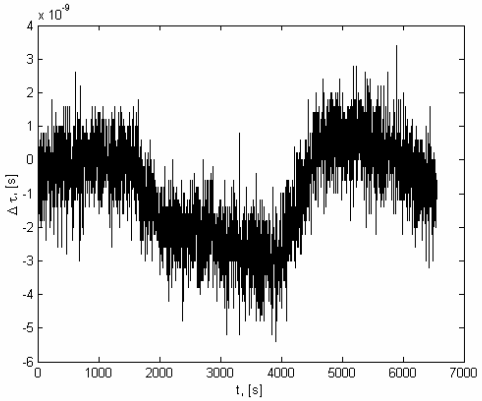
- Earlier days every major city had its own solar time.
- Due to transportation and communication in the first half of the 19th century local times has to be synchronised.
- In the 1840-1860s in almost all European countries, nationwide uniform time zones have been established.
- A global time zone system was first proposed in 1879 by the Canadian railway engineer Sir Sandford Fleming as a railway time.
- At the International Meridian Conference in October 1884 in Washington DC the earth was divided into zones 24 hours of each 15 degrees of longitude.

Synchronization
- distributed radar systems -

- Time
  - Signal transmission
  - Antenna direction
- Frequency
- Phase
- Stable oscillators
  - High stability quartz osc.
  - Atomic clocks
- Direct synchronization
  - Cable or fibre
  - LOS comm. Link
- Indirect synchronization (GNSS: GPS, GALILEO)

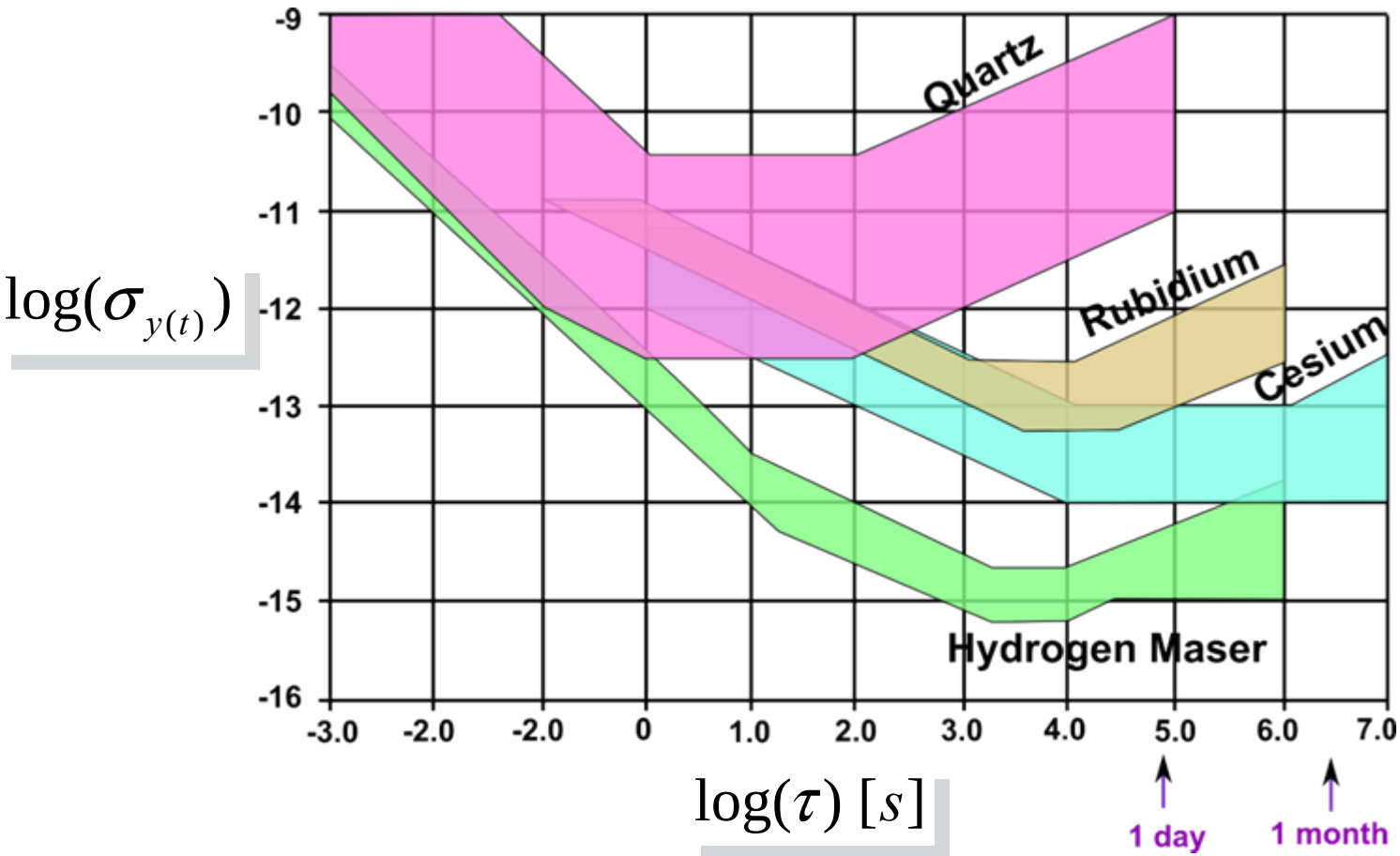






Synchronization

- Oscillator Stability vs Frequency Standards -



Synchronization

- Comparison of various stable oscillators at 10MHz -

	TCXO	OCXO	OCXO(BVA)	MCXO	Rubidium	Cesium	GPS
temperature stability	$1{\cdot}10^{-6}$	$2{\cdot}10^{-8}$	$1{\cdot}10^{-10}$	$2{\cdot}10^{-8}$	$2{\cdot}10^{-8}$	$2{\cdot}10^{-8}$	—
drift per day	$1{\cdot}10^{-8}$	$1{\cdot}10^{-10}$	$5{\cdot}10^{-12}$	$5{\cdot}10^{-11}$	$5{\cdot}10^{-13}$	$3{\cdot}10^{-14}$	$3{\cdot}10^{-14}$
short-time stability $\sigma_y(\tau)$	$1{\cdot}10^{-9}$	$1{\cdot}10^{-12}$	$5{\cdot}10^{-13}$	$1{\cdot}10^{-10}$	$5{\cdot}10^{-12}$	—	—
1s	$1{\cdot}10^{-10}$	$1{\cdot}10^{-11}$	$1{\cdot}10^{-12}$	$2{\cdot}10^{-8}$	$1{\cdot}10^{-11}$	$6{\cdot}10^{-11}$	—
100 s	$3{\cdot}10^{-10}$	$1{\cdot}10^{-11}$	$1{\cdot}10^{-12}$	$2{\cdot}10^{-8}$	$1{\cdot}10^{-13}$	$6{\cdot}10^{-12}$	—
1 day	$1{\cdot}10^{-12}$	$3{\cdot}10^{-12}$	$3{\cdot}10^{-12}$	$5{\cdot}10^{-10}$	$1{\cdot}10^{-13}$	$6{\cdot}10^{-12}$	—
£ @ 1Hz	-50	-100	-122	-115	-80	-85	—
£ @ 10Hz	-80	-130	-137	-135	-98	-125	—
£ @ 100Hz	-110	-140	-145	-145	-137	-135	—
£ @ 1kHz	-120	-145	-156	-150	-150	-140	—

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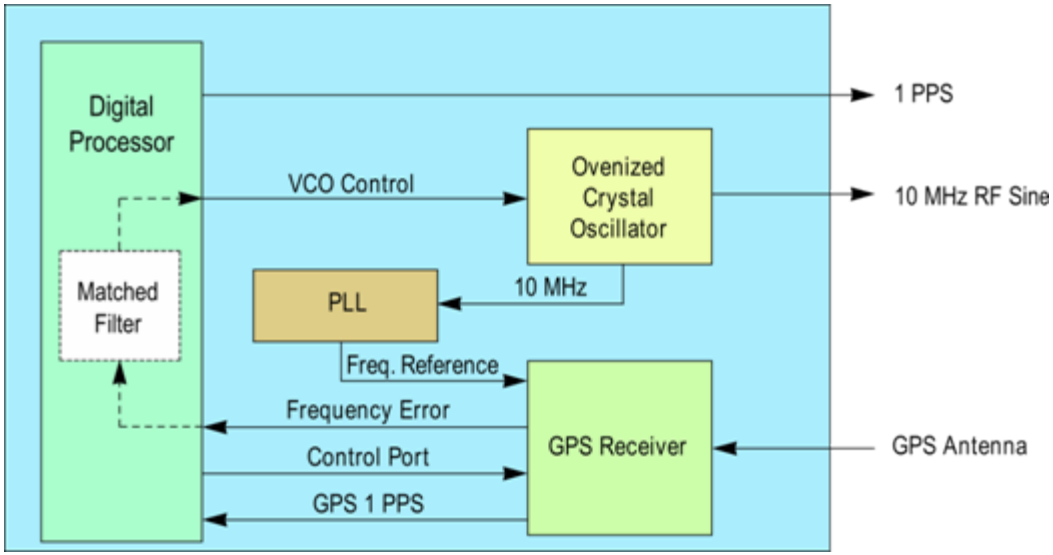
Disciplined crystal oscillator

- Principle :
- use of the GPS 1PPS to estimate the frequency drift of the oscillator and then tune the frequency by modifying the control voltage.
- very high time constant (a few hours) do not degrade the short term characteristics.

Potential oscillators:
TCXO, OCXO and possibly Rubidium



Synchronization
- Requirement -

- Required time stability depends on update interval:

$$Time\ stablity \leq \frac{\Delta\tau}{T_{(update\,interval)}}$$

  - If indirect time synchronization takes place, by introducing an additional time reference, the time stability has be an order of 2 higher
    - Example: $\Delta\tau$=0.1us, $T_{updateintervall}$=10s => *Time stability* = 1E-8

- For coherent signal processing, like Doppler or MTI processing, a stabile relationship is required over the integration time:

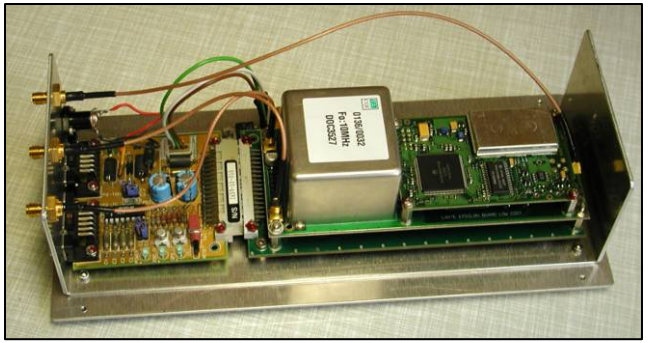
$$Phase\ stablity \leq \frac{\Delta\phi}{2\pi f\, T_{(integration)}}$$

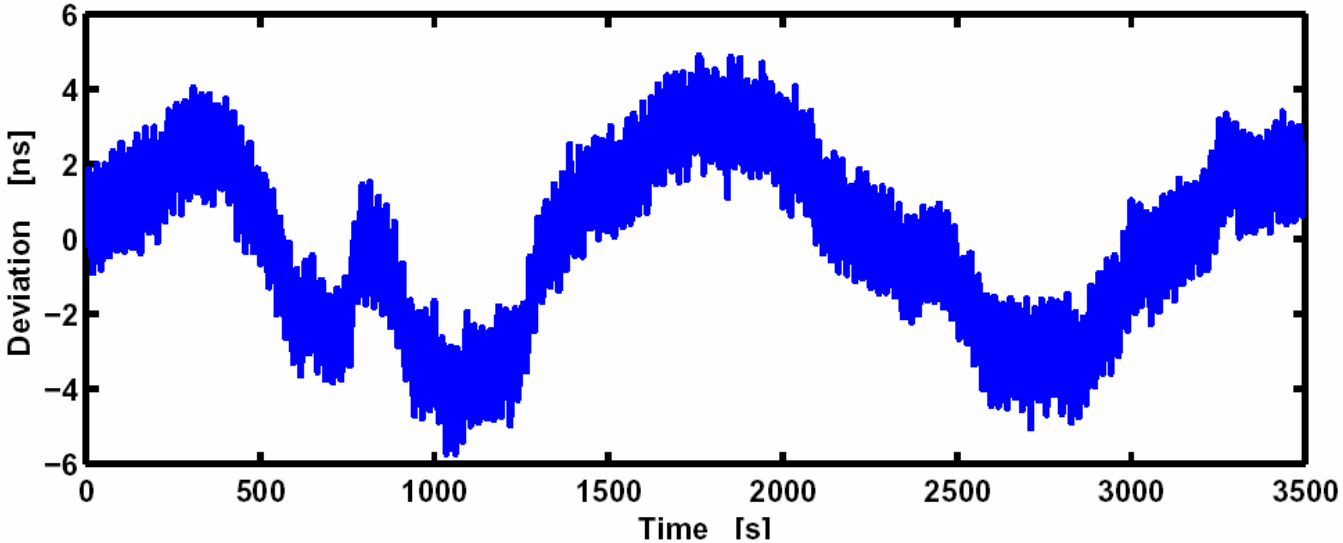
Example

- Synchronisation using 1PPS from GPS -

- With dedicated timing units disciplined by GPS a standard deviation of

  $\sigma = 15$ ns can be achieved





Coverage

- 2D view of geometry dependent coverage volume -

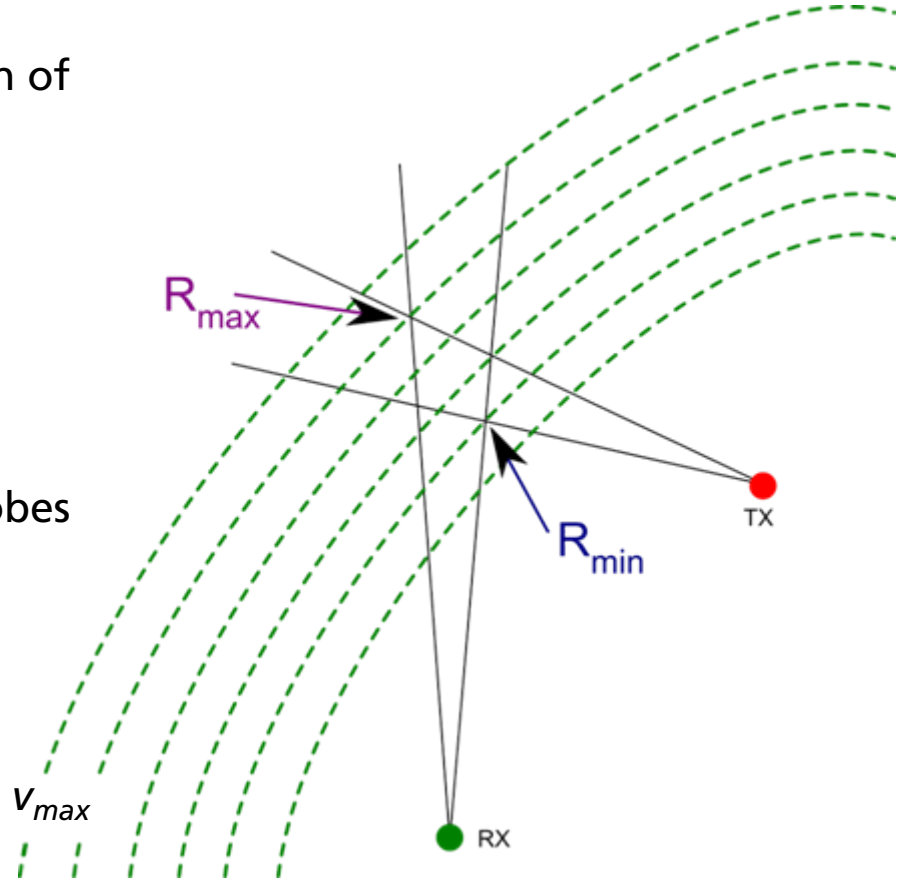
- Coverage volume given by intersection of
  - TX beam (main lobe)
  - RX beam (main lobe)
- Geometry dependent

$$[R_{min}, R_{max}]$$

  Bistatic range interval
- Assuming no signal received by side lobes

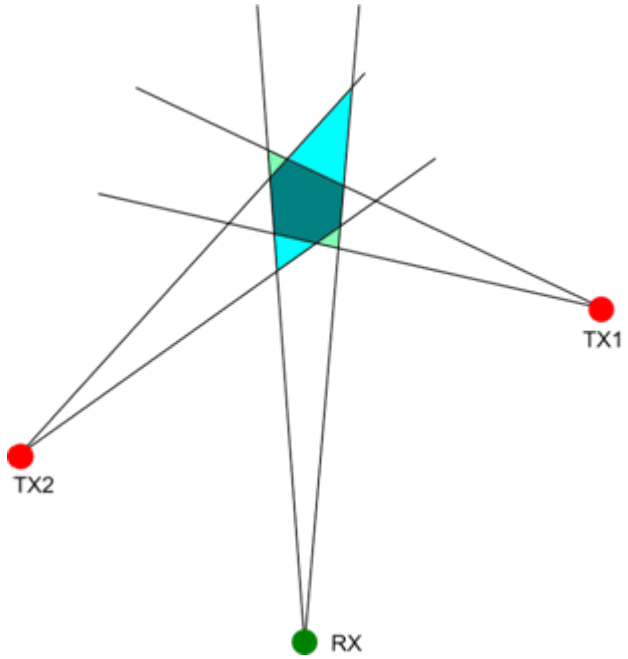
$$PRF_b = \frac{c}{R_{max} - R_{min}}$$

➡ shorter transmitted pulse
  - Increase of ambiguity range v_{max}
  - Decrease resolution: Δv

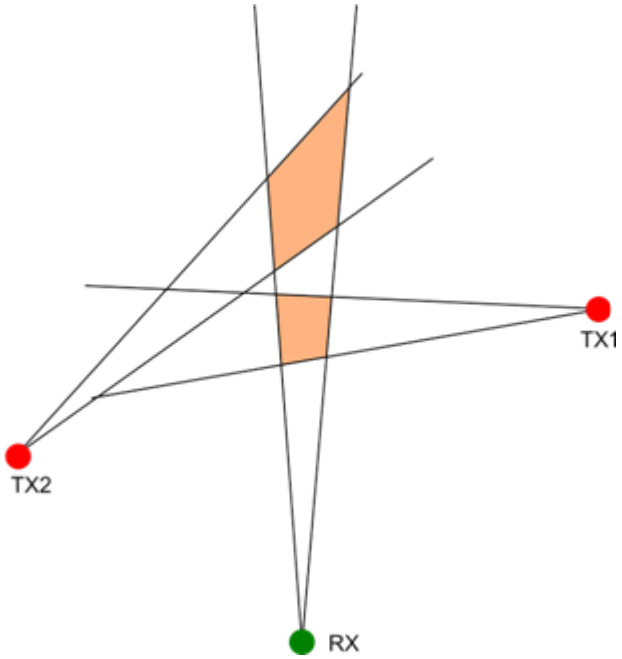


Coverage
- Antenna beam pointing -

- Possible range and velocity ambiguities if both TX transmit similar waveforms at the same center frequency



- Solution:
  - Time separation
  - Orthogonal waveforms
  - Separated range intervals



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Ambiguity function
- monostatic -

- Ambiguity function is the response of a matched filter to a signal shifted in time τ (==range r) and Doppler frequency f_D (== velocity v)

- Shows resolution, sidelobe level and structure, and ambiguities, in delay and Doppler.

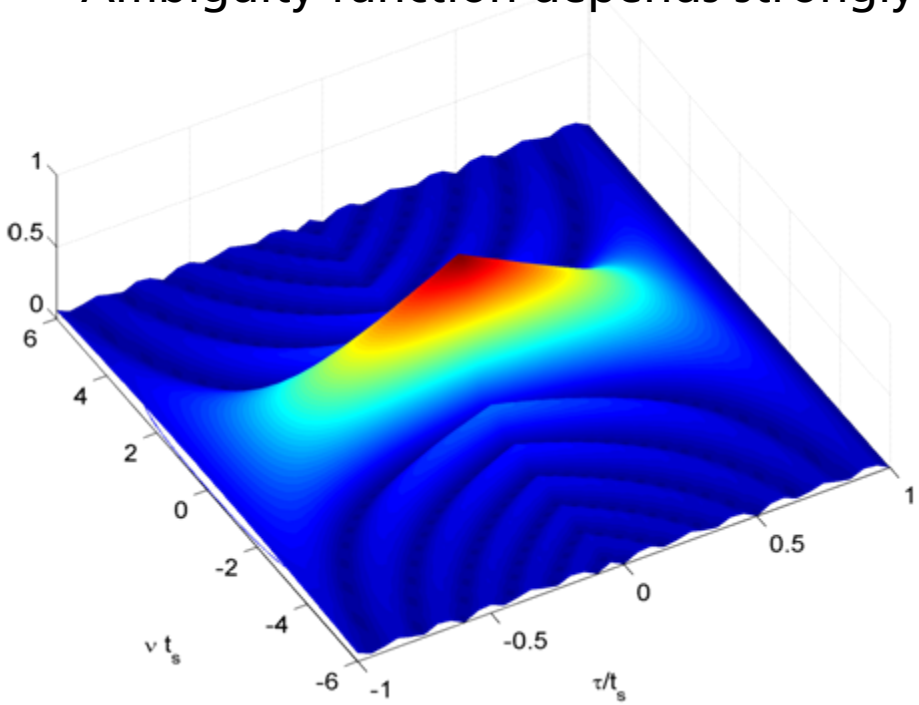
$$X(\tau, f_D) = \left| \int_{-\infty}^{\infty} s(t)\, s^*(t-\tau)\, e^{j2\pi f_D t}\, dt \right|^2$$

For narrowband signals fulfilling the condition: $2vBT$ << c

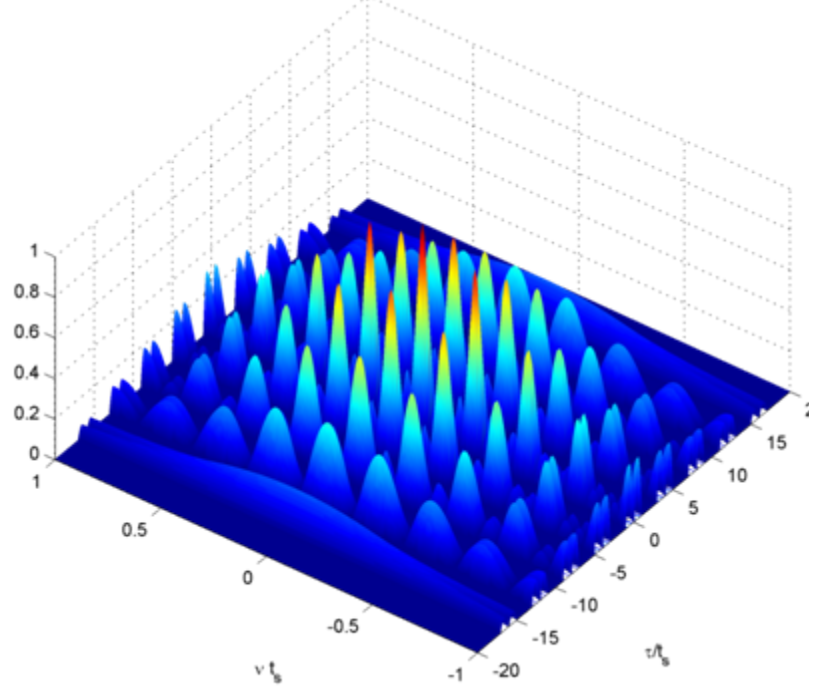
P.M. Woodward, *Probability and Information Theory, with Applications to Radar*, Pergamon Press, 1953; reprinted by Artech House, 1980.

Ambiguity function
- monostatic -

- Ambiguity function depends strongly on the used waveform …



Ambiguity function of a rectangular pulse (pulse width t_s)



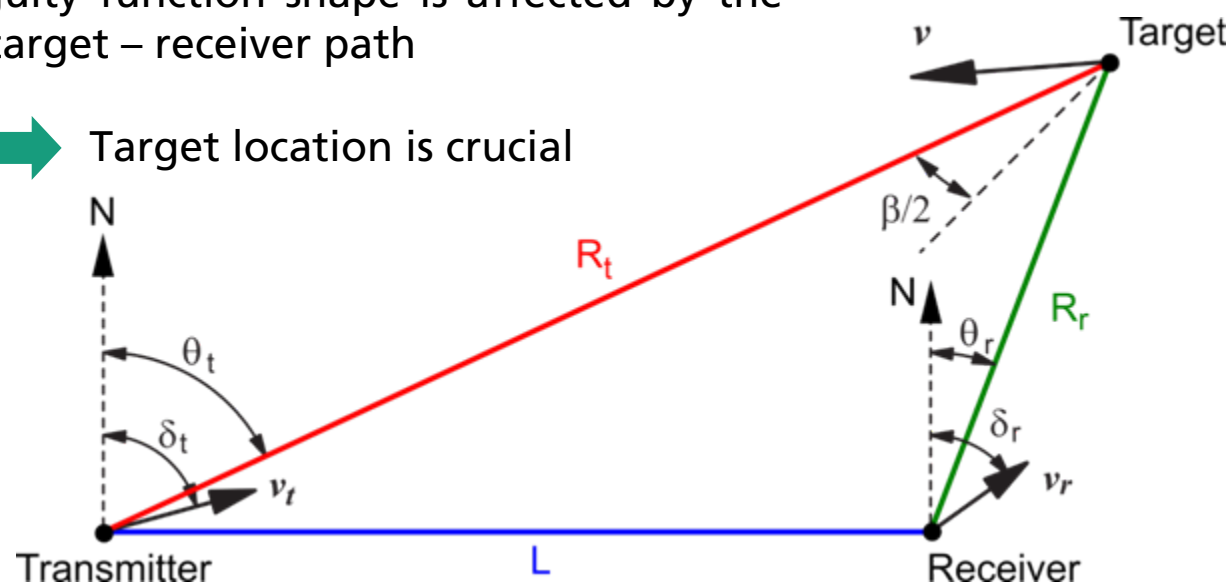
Ambiguity function of a train of 5 rectangular pulses

Ambiguity function
- bistatic -

- For bistatic geometry the simple linear relationship between time delay τ and range r and between target velocity v and Doppler shift f_D is no longer valid.

Bistatic ambiguity function shape is affected by the transmitter – target – receiver path

Target location is crucial



Ambiguity function
- bistatic -

- As the locations of TX, RX and target has to be taken into account the bistatic ambiguity function $X(\tau, f_D)$ can be written as:

$$\left|X(R_{R_h}, R_{R_a}, V_h, V_a, \theta_R, L)\right|^2 = \left|\int_{-\infty}^{\infty} s(t-\tau_a(R_{R_A}, \theta_R, L))\, s^*(t-\tau_h(R_{R_h}, \theta_R, L)) \cdot e^{j2\pi f_D t}\, dt \cdot e^{-j(2\pi(f_{Dh}(R_{R_h}, \theta_R, L) - f_{Da}(R_{R_a}, \theta_R, L)t)}\, dt\right|^2$$

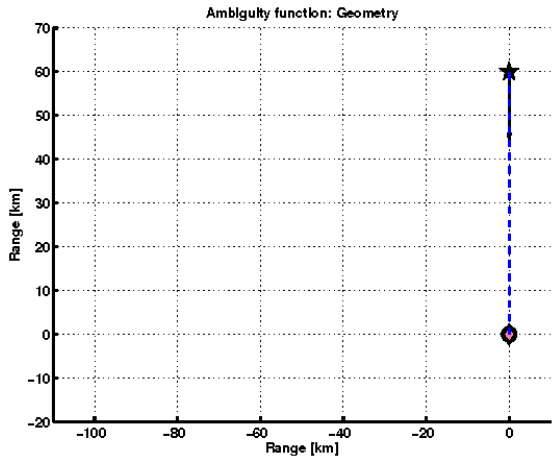
a = actual value | h = hypothetical value

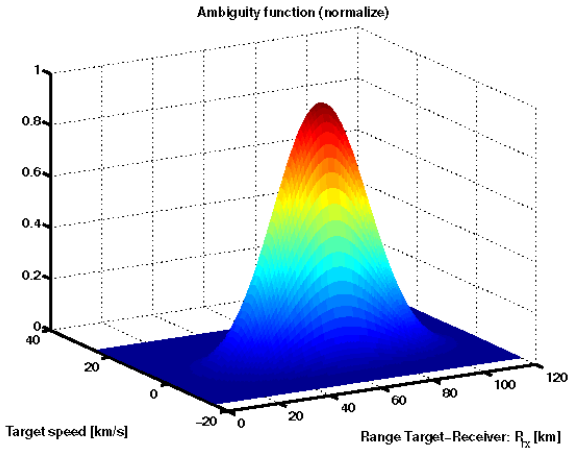
Tsao, T., Slamani, M., Varshney, P., Weiner, D., Schwarzlander, H. and Borek, S. ‘Ambiguity function for bistatic radar’; *IEEE Trans. Aerospace and Electronic Systems*, Vol.AES-33, pp1041-1051,1997.

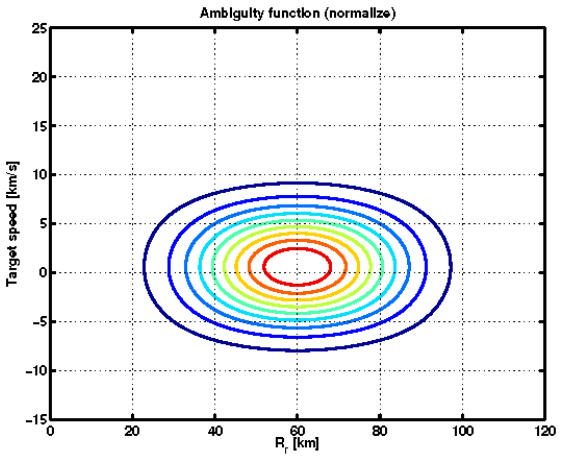
Ambiguity function
- bistatic -

- For the following examples a Gaussian shaped pulse is considered, which can be described by:

$$s(t) = \left(\frac{1}{\pi T^2}\right)^{1/4} \exp\left(-\frac{t^2}{2T^2}\right) \qquad -\infty \le t \le \infty$$







Pulse duration T=120 µs, time delay τ = 400 µs, and centre frequency f_c = 50 MHz

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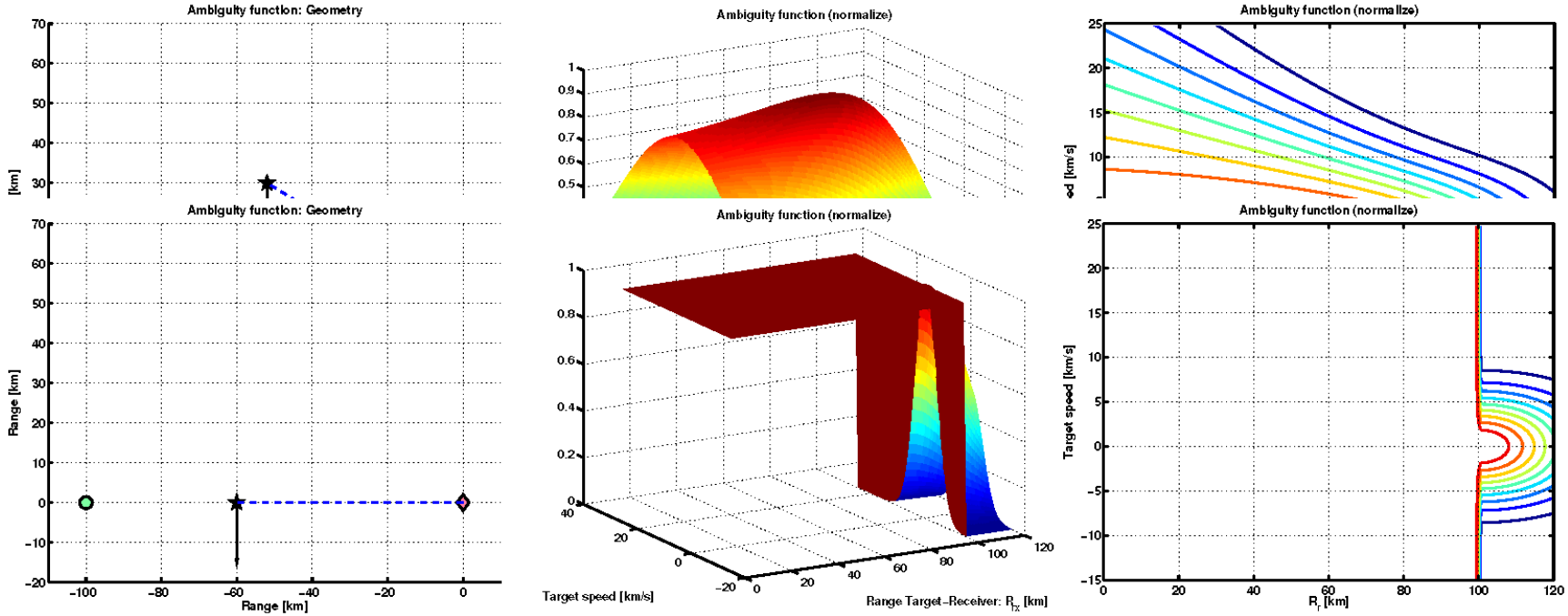
Ambiguity function
- bistatic -



Ambiguity function
- multistatic / MIMO radar -

For a multistatic network the ambiguity function can be determined by using the following three steps (coherent network, similar waveforms, RCS is similar to all Rx)

- For each transmitter-receiver-pair the bistatic ambiguity function has to be calculated
- Calculating a weighting factor according to received signal intensity

$$P_{ij} = \frac{P_i G_i G_j \lambda^2 \sigma}{(4\pi)^3 (R^2{}_{tx_i \to t} R^2{}_{t \to rx_j})}$$

$$w_{ij} = \frac{P_{ij}}{\max(P_{ij})}$$

- To formulate multistatic radar ambiguity function using the results from previous calculations:

$$X_{multi} = \left| \frac{1}{M^2 N^2} \sum_{i=1}^{M} \sum_{j=1}^{N} w_{ij} X_{ij} \right|^2$$

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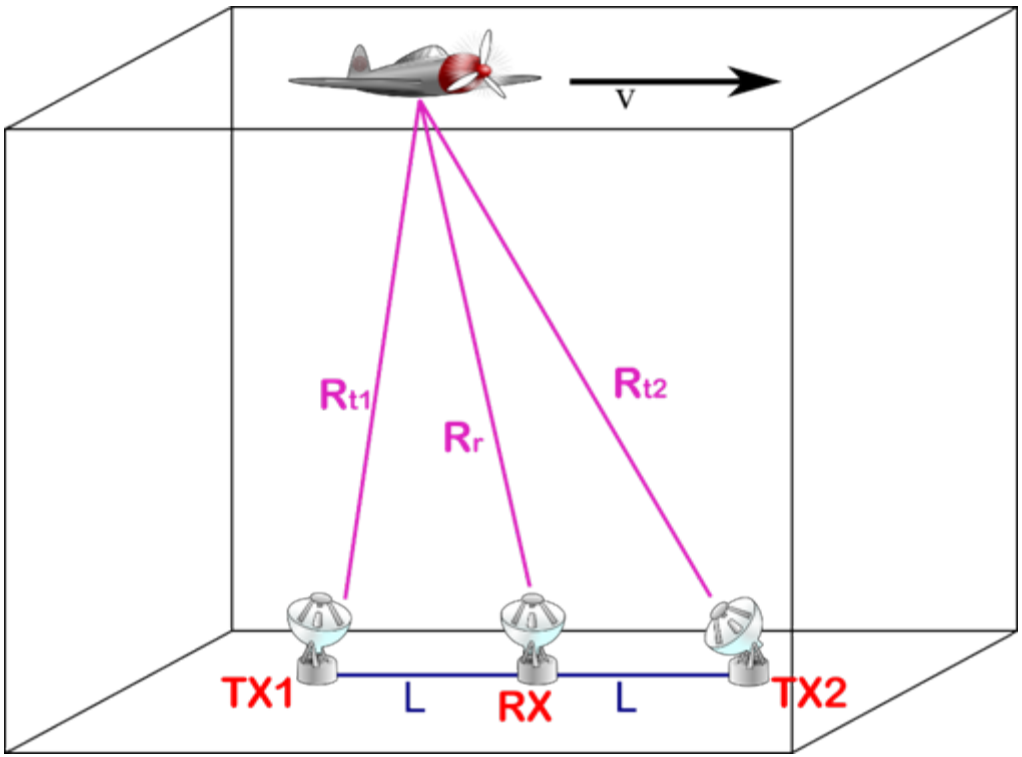
Ambiguity function

- 3D constellation for 2 TX and 1 RX -



Each bistatic pair

Delay

$$\tau = \frac{|R_t| + |R_r|}{c}$$

Doppler

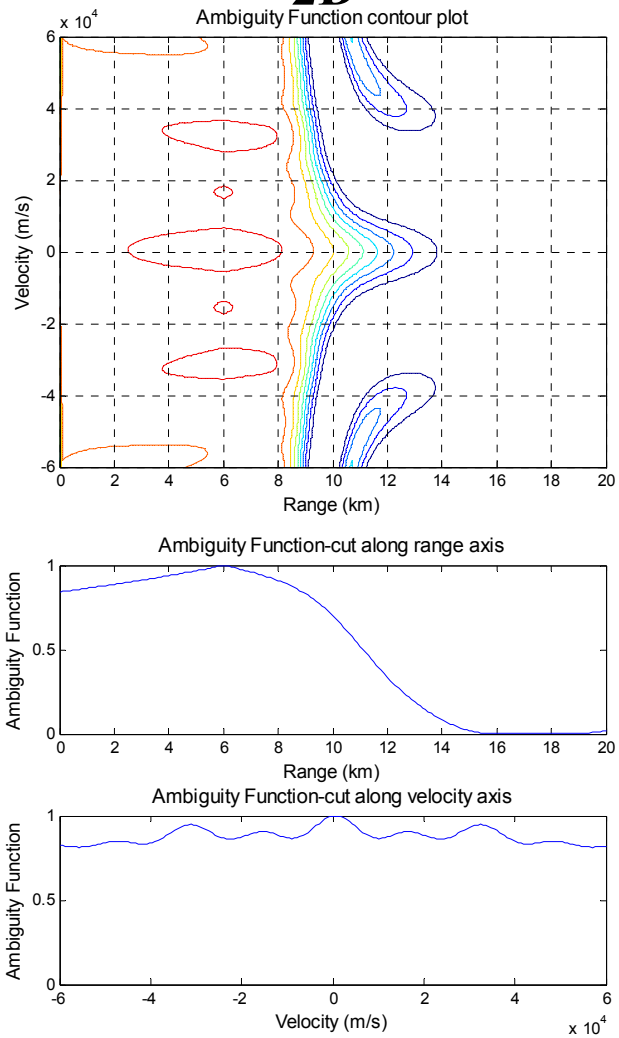
$$f_b = \frac{1}{\lambda}\left[\frac{d}{dt}(R_t + R_r)\right] = \frac{1}{\lambda}\left[\frac{R_t \bullet V}{|R_t|} + \frac{R_r \bullet V}{|R_r|}\right]$$

Simulations constraints: pulse length=40us, period=100us, f_c=48MHz, v_{target}=600m/s, Baseline TX<->RX = 10km

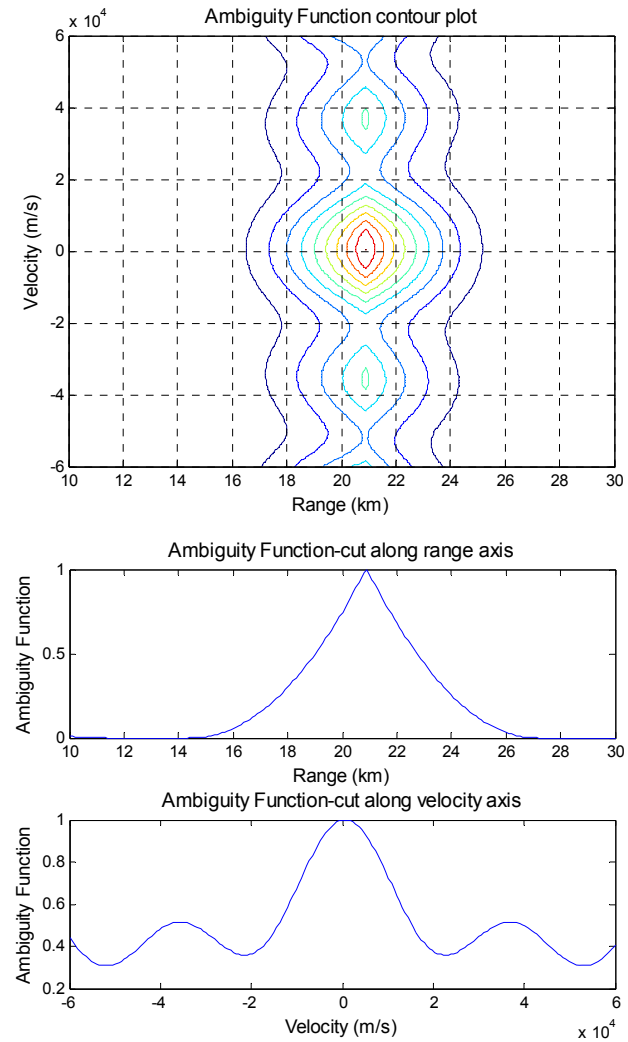
Ambiguity function

- 3D constellation for 2 TX and 1 RX, Integration over 3 pulses -

2D



3D-H=20km

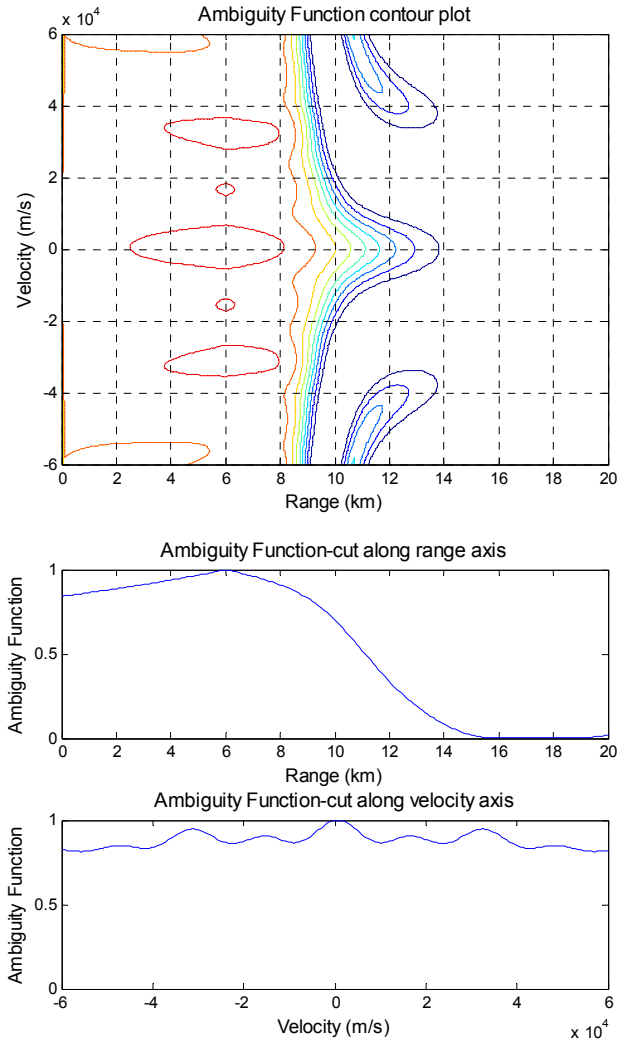


Courtesy of C. Baker

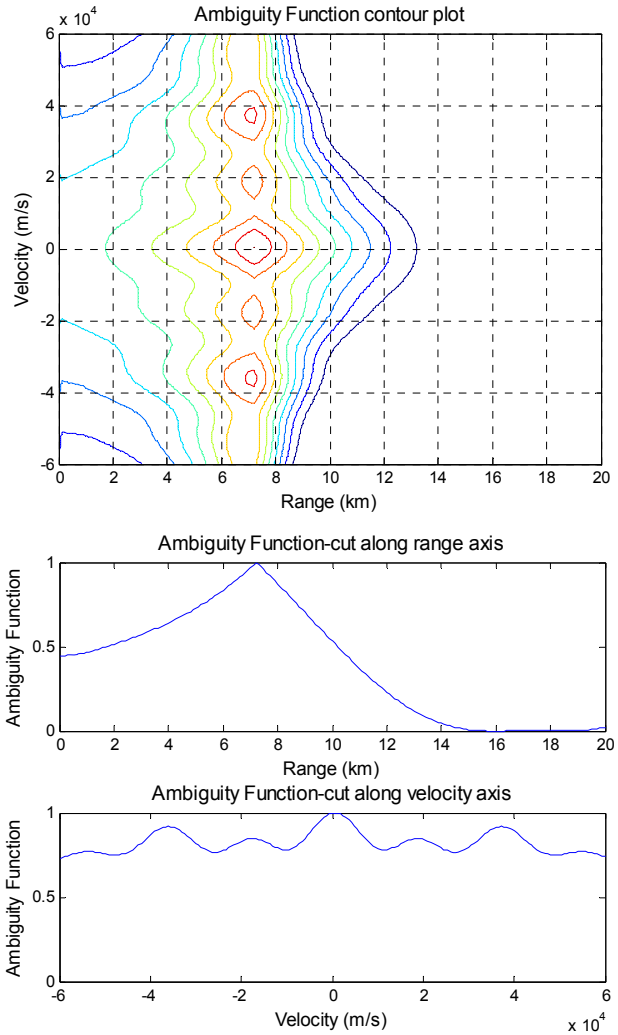
Ambiguity function

- 3D constellation for 2 TX and 1 RX, Integration over 3 pulses -

2D



3D-H=4km



Courtesy of C. Baker

Multistatic Challenges

- Received Signal -

- Received signal is in general composed of
  - Direct signal
  - Multipath signals
  - Reflected signal from target
  - noise

$$s_r(t) = A_d\, s(t-\tau_d) + \sum_{m=0}^{M} A_m\, s(t-\tau_m) + \sum_{n=0}^{N} A_n\, s(t-\tau_n)\, e^{j\,2\,\pi\, f d_n\, \tau_n} + n(t)$$

- Biggest issue for bistatic/passive radar is the demanded dynamic range of the receiver, as the direct signal is only attenuated by 1/Baseline^2

- Echos exhibits an attenuation of $\sim \frac{\sigma}{R_T^2 + R_R^2}$ with $R_T + R_R \geq L$

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Direct Signal Interference

- Direct Signal Noise Ratio

$$DNR = \frac{P_{tx}\, G_{tx}(\varphi_{rx}, \theta_{rx})\, G_{rx}(\varphi_{tx}, \theta_{tx})\, \lambda^2}{(4\pi)^2\, R_{tx \to rx}^2\, k\, T_0 B\, F\, L}\, G_{int}$$

- Signal-to-direct-signal power ratio:

$$SDR = \frac{G_{tx}(\varphi, \theta)\, G_{rx}(\varphi, \theta)}{G_{tx}(\varphi_{rx}, \theta_{rx})\, G_{rx}(\varphi_{tx}, \theta_{tx})} \left(\frac{R_{tx \to rx}}{R_{tx}\, R_{rx}} \right)^2 \frac{\sigma_b}{4\pi}$$

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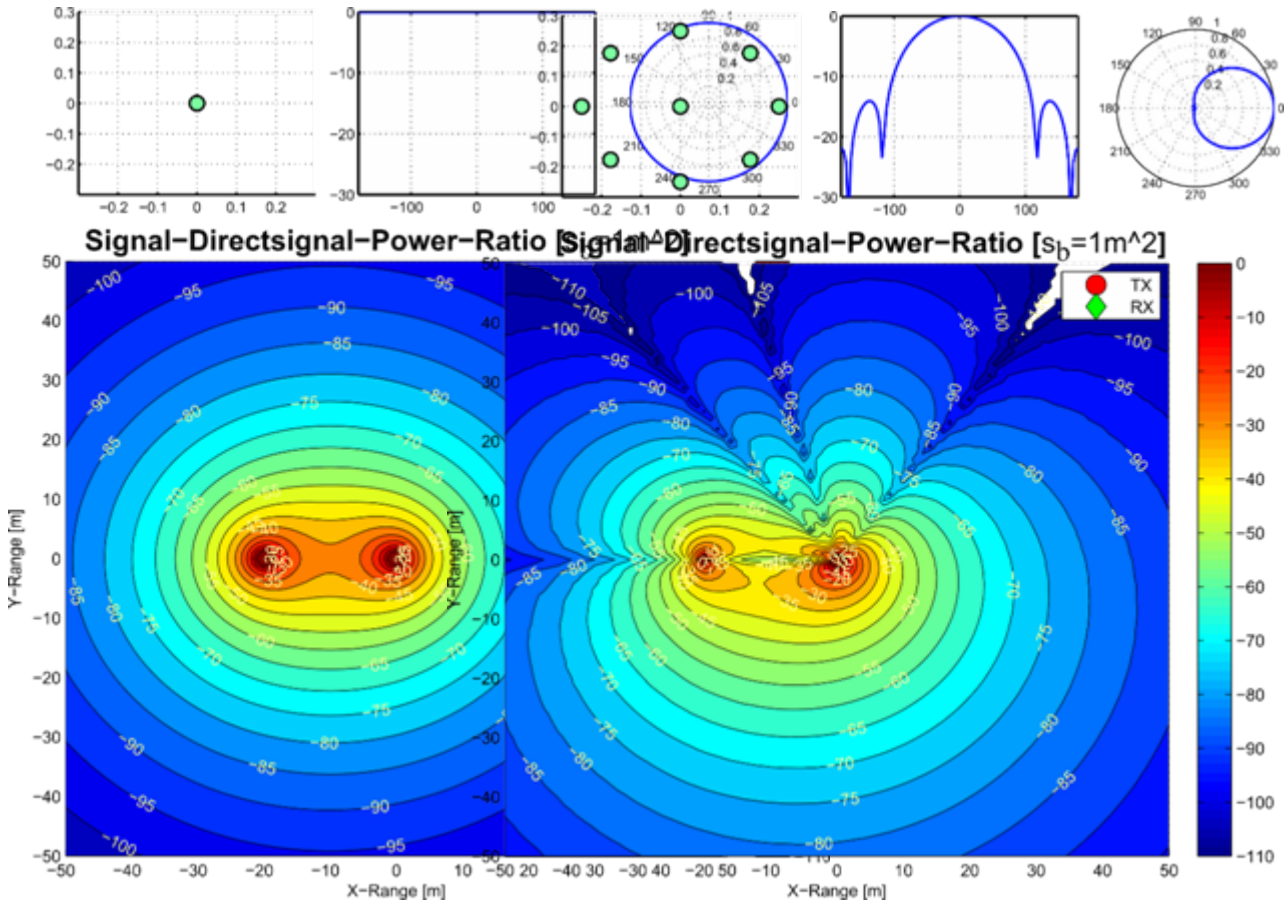
Direct Signal Interference



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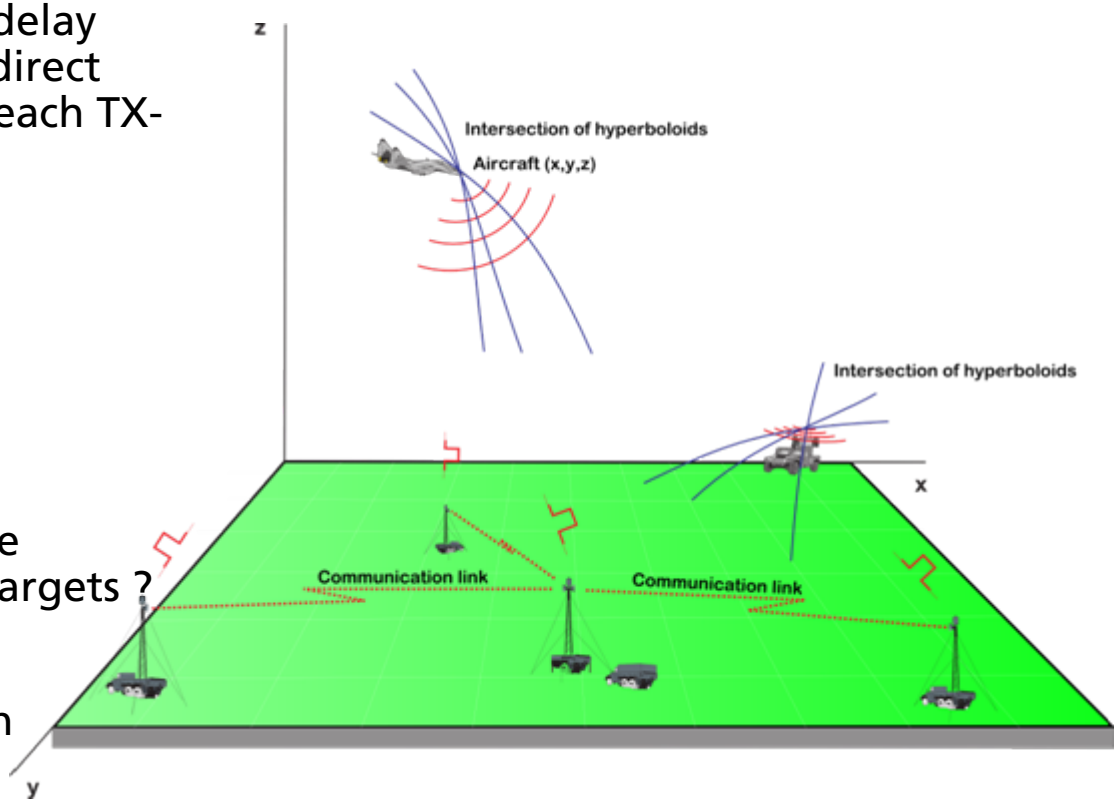
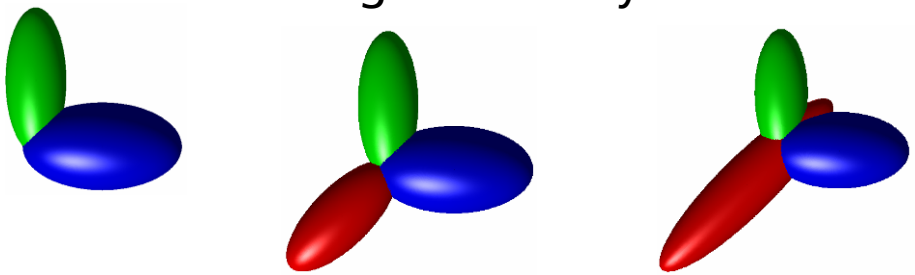
Target localisation

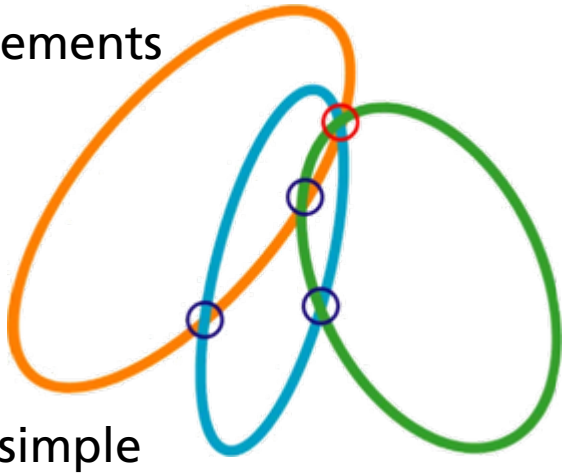
- A multistatic radar system can measure:
  - Bistatic range (from delay difference between direct signal and echo) for each TX-RX pair
  - Echo Doppler
  - Echo angle of arrival
  - from one or more transmissions
- How can such measurements be combined to locate and track targets ?
  - Multilateration
  - Parameter estimation



Target localisation
- Multilateration -

- Multilateration system (hyperpolic positioning)
  - Input from severall TX-RX radars
  - Processing based only on time delay measurements





  - Association of detections
    - Single target observed by all systems -> simple
  - Multiple targets
    - Large set of combinations
    - Ghost targets

UNTIL IT GETS REALLY UGLY

- (Paul Howland's NATO test bed) -

Works well for a single target. Changes dramatically for multiple targets.

RX: (0,0)

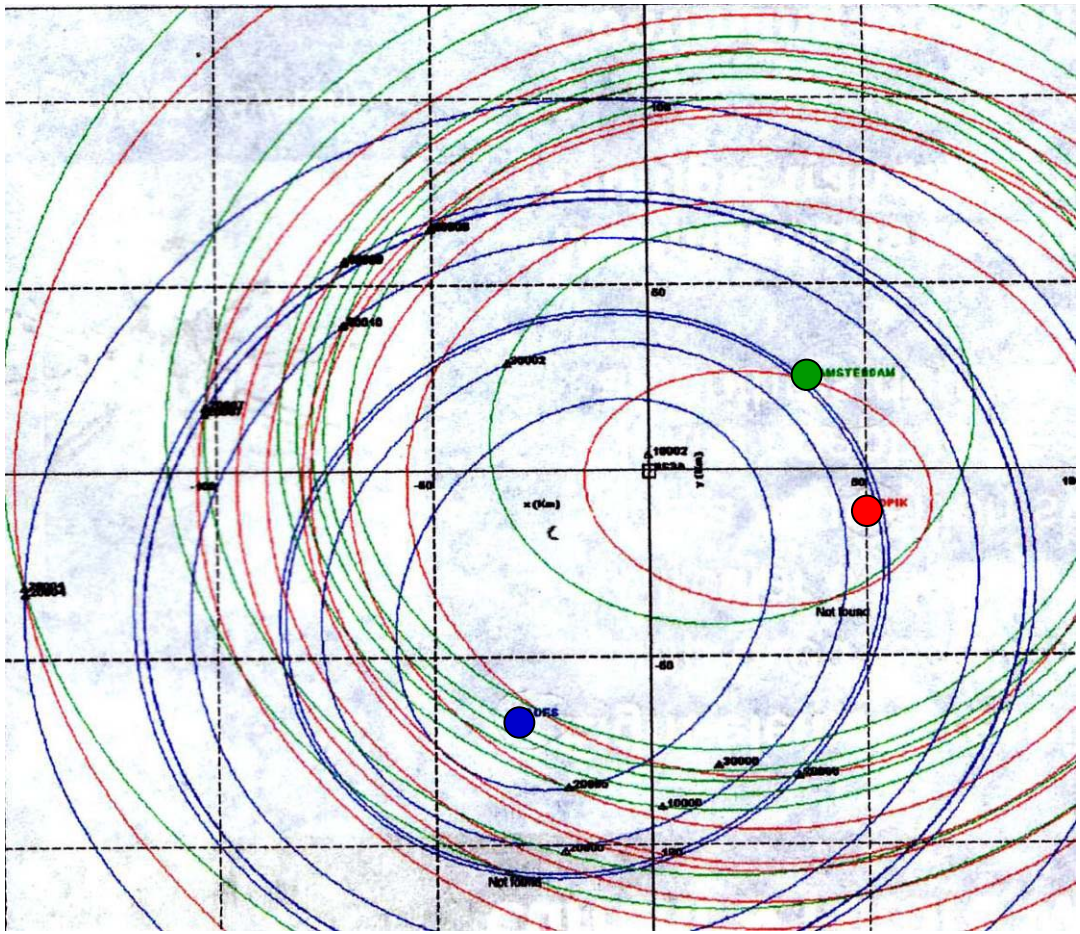
TX: 3 (Red, blue, green)

Targets: 9

True targets: Located by ATC radars

Ghosts: All other intersections

AND THEY MUST BE EXCISED



Courtesy of P. Howland

Target localisation
- Multilateration -

- 3 TX-RX pairs needed for localizing target in 2D (3D needs one additional TX-RX pair)
- Improvement can be achieved by adding additional TX-RX pairs and/or by averaging TDOA over several measurements

- Accuracy of multilateration is a function of several parameters:
  - Antenna / sensor geometry of RXs and TXs
  - Timing accuracy of the receiver systems, i.e. Thermal stability of local reference clock
  - Accuracy of frequency synchronisation of transmitted signal with received signal, as e.g. Diffraction of reflection changes phase of the signal thus indication deviation from line of sight (multipath effects)
  - Bandwidth of emitted pulse and thus the rise-time of the pulse with pulse-coded signals in transmission

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Target localisation I

- Parameter estimation -

- The second approach to determine the position of the target is to estimate the parameters of the received lowpass filtered signal:

$$r_l(t) = \sum_{k=1}^{M} \sigma s_k(t - \tau_{lk}) e^{-j2\pi f_c \tau_{lk}} + n_l(t)$$

- Can be used for non-coherent and coherent single-type sensor networks

- Parameters can be estimated with the **b**est **l**inear **u**nbiased **e**stimator (BLUE) if a linear regression model exists. If the errors have expectation zero, are uncorrelated and have equal variances the BLUEstimation of the coefficients is given by the ordinary least squares estimator.
- The **b**est **l**inear **u**nbiased **p**redictions (BLUP), which is similar to BLUE, was derived by Carles Roy Henderson in 1975.

Henderson, C.R. (1975). "Best linear unbiased estimation and prediction under a selection model". Biometrics 31 (2): 423–447.

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Target localisation II

- Parameter estimation, coherent mode -

- The goal of the estimator is to determine the target position X=[x,y]' .
- This can be estimated directly by formulating the maximum likelihood estimator (MLE) associated with

$$r_l(t) = \sum_{k=1}^{M} \sigma s_k(t - \tau_{lk}) e^{-j2\pi f_c \tau_{lk}} + n_l(t)$$

- or by determining the time delay

$$\tau_{lk} = \frac{1}{c}\left[\sqrt{(x_{tk} - x)^2 + (y_{tk} - y)^2} + \sqrt{(x_{rl} - x)^2 + (y_{rl} - y)^2}\right]$$

- This can be done coherently or non-coherently. It is imperative the local time references of each involved node has to be synchronized to a reference clock.

- The target localization processing uses then the well-established multilateration principle.

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Linear Perturbation Model

- BLUE needs a linear model, hence we to perform a linearization, as time-delay is a non-linear function of target location!

  $\tau = \tau_0 + \tau_{linear}$

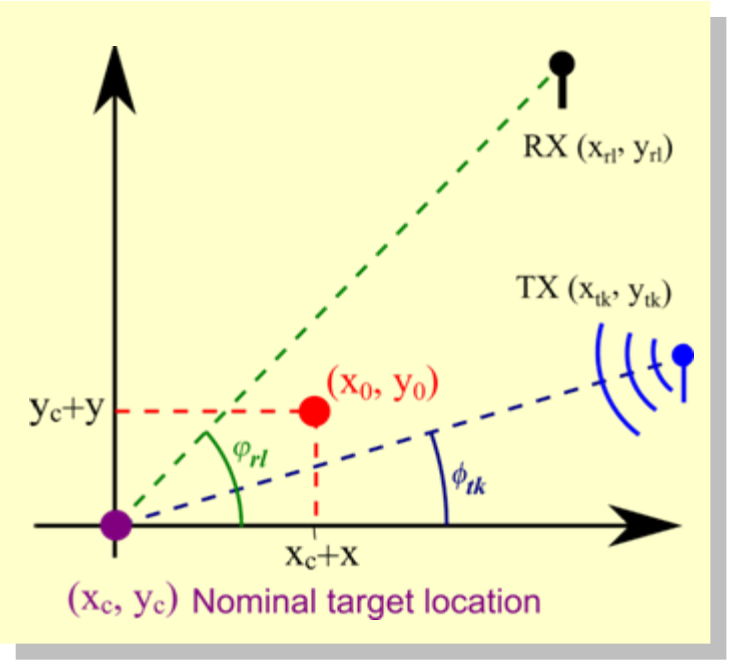
- Target is modulated as point scatterer showing a unknown homogeneous, complex RCS

  $\sigma = \sigma_r + j\,\sigma_i$

- Linear perturbation model: linearize around the expected location (x_c, y_c)

$$\tau_{lk}(x) \approx -\frac{x}{c}\left(\cos\phi_{tk} + \cos\varphi_{rl}\right) - \frac{y}{c}\left(\sin\phi_{tk} + \sin\varphi_{rl}\right)$$

ϕ_{tk}, φ_{rl}: azimuth angles



BLUE Localisation

Target localization :

coherent case

- **ML** estimate the unknown parameters: $\mu_{lk} = \max_{\tau} \left| \int r_l(t)\, s_k^*(t-\tau_{lk})\, e^{-j2\pi f_c \tau_{lk}}\, dt \right|$

  $\theta = [x, y, \sigma]^T$; target reflectivity σ is nuisance parameter

- The estimated time delays μ serve as "observations" of the signal model

$$\mu = \mathbf{D}\theta + \varepsilon$$

μ is the observable time delay vector, θ the vector of the unknown parameter and ε the MxN noise vector, and $\mathbf{D}$ relation matrix between μ and θ

- Relation between time delay and target location: The locus of constant sum of time delays "transmitter k – target" and "target – receiver ℓ" is an ellipse
- The target location is found at the intersection of ellipses formed with pairs of transmitter-receiver as foci
- BLUE target localization, and
  BLUE covariance matrix of the estimate

$$\boldsymbol{\theta}_{BLUE} = (\mathbf{D}^T \mathbf{C}_\varepsilon^{-1} \mathbf{D})^{-1} \mathbf{D}^T \mathbf{C}_\varepsilon^{-1} \mu$$

$$\mathbf{C}_{\boldsymbol{\theta}_{BLUE}} = (\mathbf{D}^T \mathbf{C}_\varepsilon^{-1} \mathbf{D})^{-1}$$

H. GODRICH, A.M. HAIMOVICH, R.S. BLUM, "Target localization techniques and tools for multiple-input multiple-output radar", IET Radar, Sonar & Navigation, 2009, Vol. 3, Iss. 4, pp. 314-327

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BLUE Features

- For BLUE the estimation error covariance matrix is:

$$\mathbf{C}_{BLUE} = \frac{c^2}{8\pi^2 \,\mathrm{SNR}(f_c^2 + \beta^2)} \cdot \frac{1}{u_B} \cdot \mathbf{G}_B$$

- The term u_B and the matrix $\mathbf{G}_B$ incorporate the effect of sensor locations relative to the target, β is the effective bandwidth, f_c the center freq.
  - For the linear, Gaussian model, BLUE is asymptotically (long observation time) optimal, i.e., meets CRLB
  - Localization error is approximately proportional to $1/f^2_c$ and $1/\beta^2$

- We are interested in the variances σ^2_x, σ^2_y of the estimates of the x and y coordinates of the target ($\mathbf{C}_{BLUE}[1,1]$ & $\mathbf{C}_{BLUE}[2,2]$) and is there a good way to show the relation between sensor locations and localisation error?

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Position Dilution Of Precision (PDOP)

- Position Dilution Of Precision (PDOP) metric is commonly used in global positioning systems (GPS) in mapping the attainable location accuracy for a given constellation of GPS satellites
- PDOP enables to separate the effect of geometry from the effect of measurement error
- For a given linear measurement model of time-delay with noise variance a corresponding dilution of precision can be defined. For the two dimensional case, where X = (x; y), it is:

$$PDOP = \frac{\sqrt{\sigma_x^2 + \sigma_y^2}}{\sigma_R} \qquad TDOP = \frac{\sqrt{\sigma_t^2}}{\sigma_R} \qquad GDOP = \sqrt{PDOP^2 + TDOP^2}$$

- where σ_R is the standard deviation of the range estimation, defined by standard deviation of the time delays σ_t, σ_x and σ_y are the variances of the localisation on the x and y axis, respectively.

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Lowest PDOP

- As BLUE and its error covariance matrix are given in closed-form the PDOP can also be calculated in closed-form. Hence, PDOP can easily be determined for a given multistatic network.
- The lowest PDOP corresponds to the most favorable geometry for the problem
- At least 3 sensors are required to resolve location ambiguity
- Assumptions for calculating PDOP:
  - A regular N-sided polygon is centered at the axis origin (x = 0, y = 0) and the target is located at its center.
  - M = N transmitting/receiving nodes located at the polygon vertices
  - The best PDOP for BLUE localization is: $$PDOP_{BLUE} = \sqrt{\frac{2}{NM}}$$
  - It can be shown that this is **the lowest attainable PDOP**

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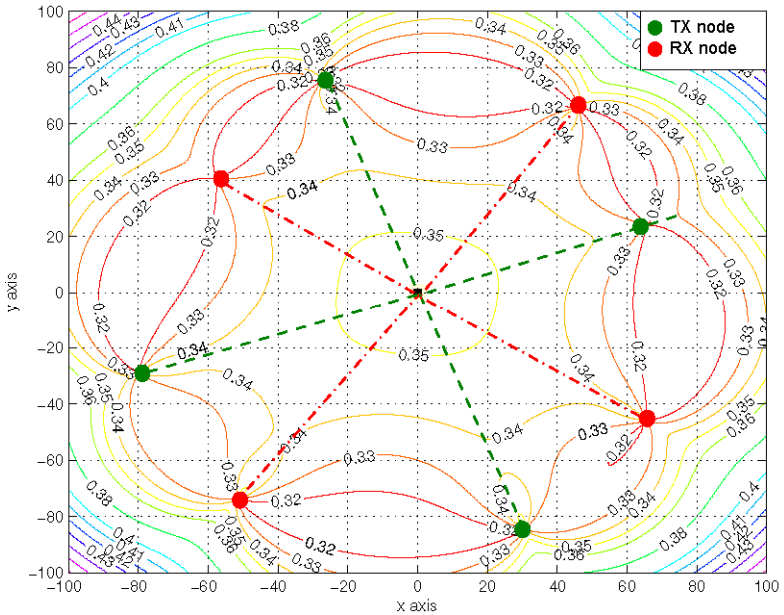
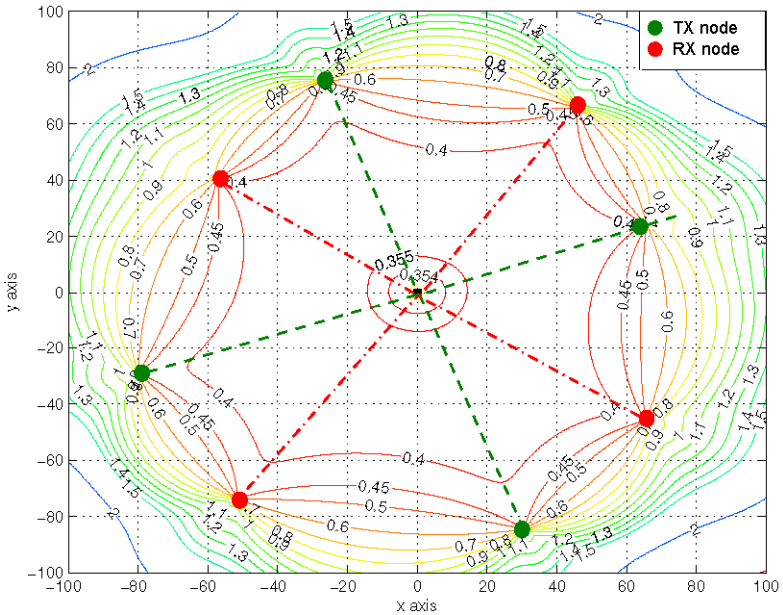
PDOP Numerical Examples

- Four transmitters and four receivers, located *nearly* symmetrically around the axis origin.



PDOP contour plot for M = N = 4
non-coherent radar network

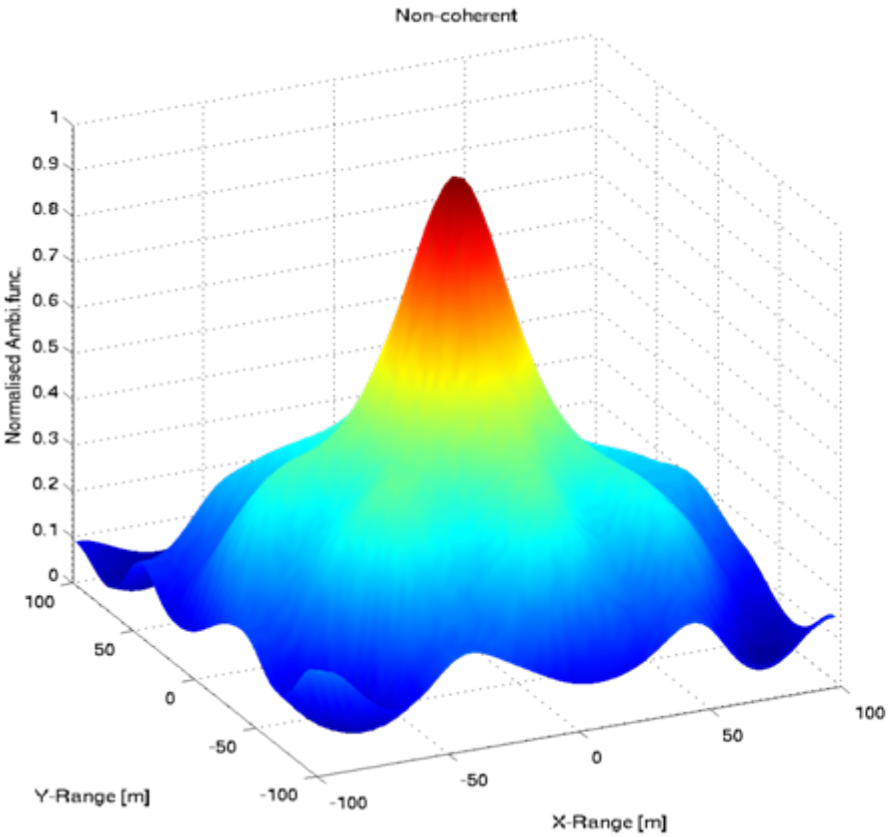


PDOP contour plot for M = N = 4
coherent radar network

Courtesy of A. Haimovich

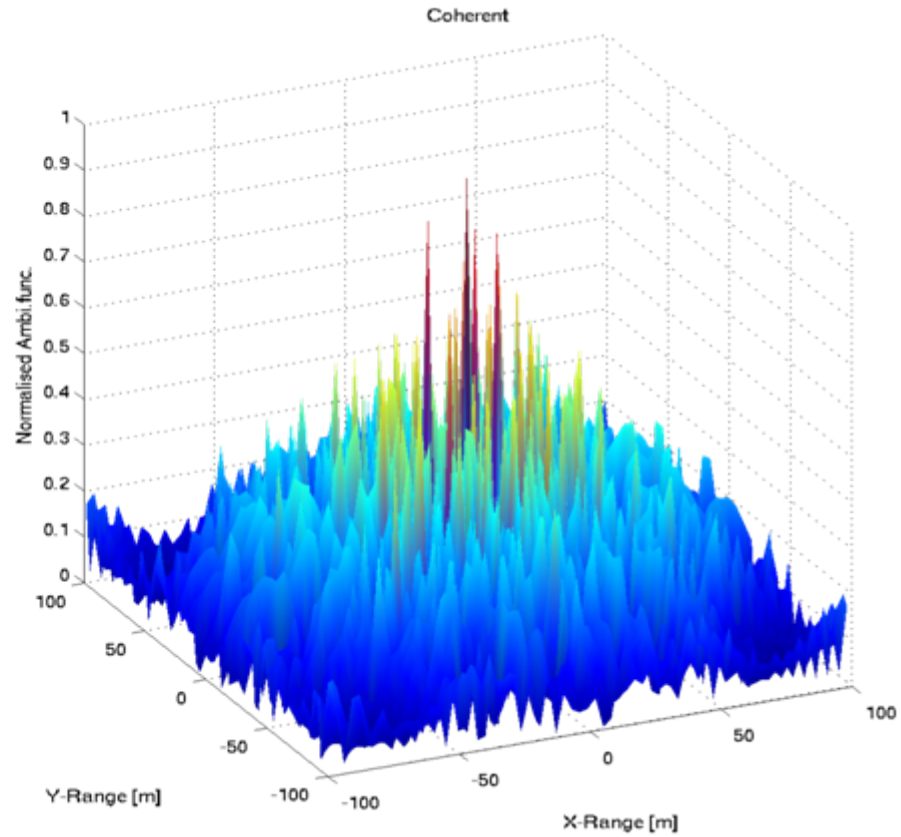
2D-Correlation for MIMO

- symmetrical constellation -



Ambiguity function plot for M = N = 4

non-coherent radar network



Ambiguity function plot for M = N = 4

coherent radar network

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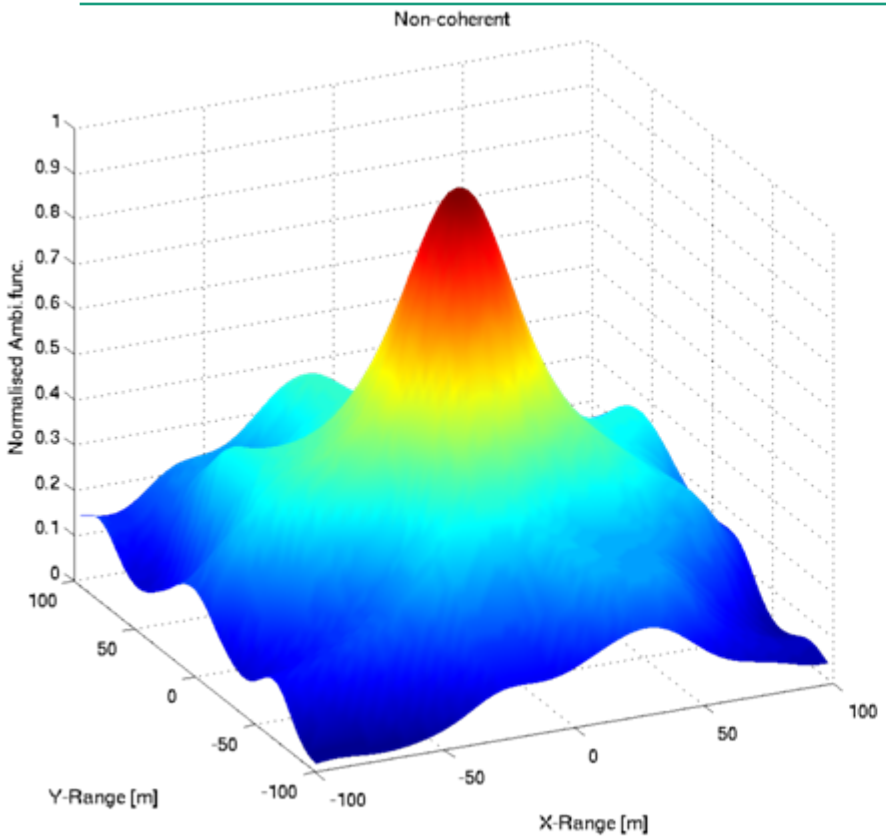
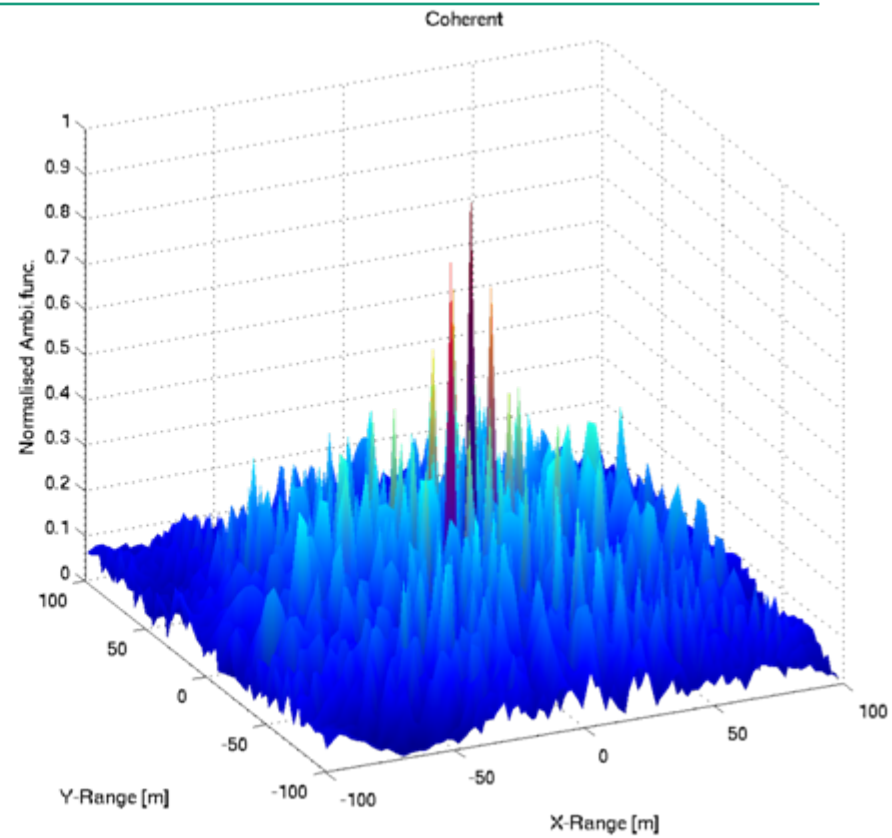
2D-Correlation for MIMO

- unsymmetrical constellation -



Ambiguity function plot for M = N = 4
non-coherent radar network



Ambiguity function plot for M = N = 4
coherent radar network

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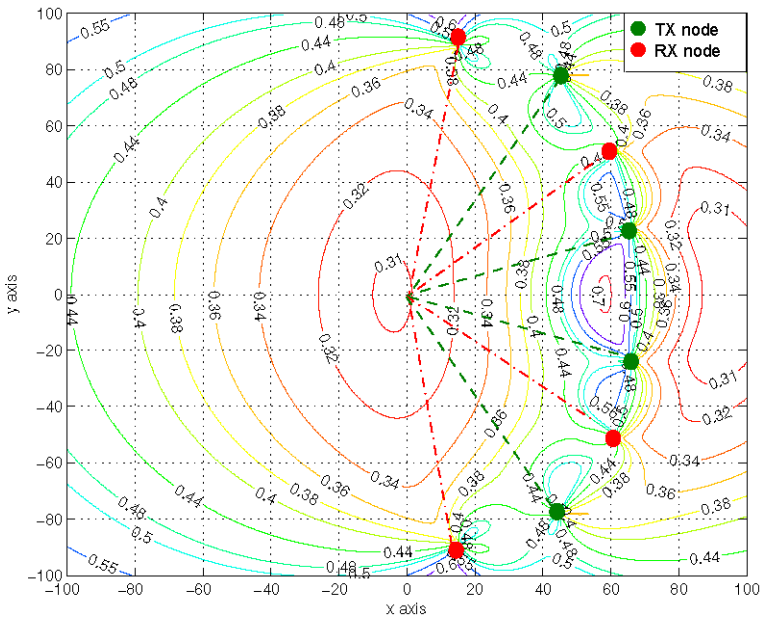
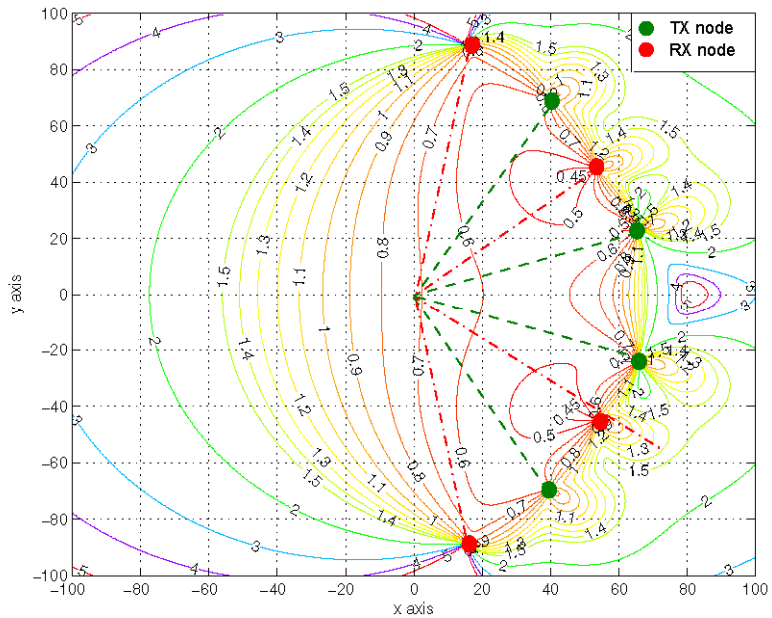
PDOP Numerical Examples

- Four transmitters and four receivers forms semicircle



PDOP contour plot for M = N = 4
non-coherent radar network



PDOP contour plot for M = N = 4
coherent radar network

Courtesy of A. Haimovich

Conclusion

- Multistatic radar networks sensitivity depends not only on radar parameters, but also on system geometry.
- Multistatic radar networks offers more flexible arrangement of system geometry than traditional monostatic systems, leading to the possibility of configuring radar nodes to form a satisfactory coverage area.
- 3D geometry has a significant effect on the ambiguity properties.
- The degradation of range and Doppler resolution shown in the two dimensional multistatic radar cases can be reduced in three dimensional multistatic radar cases
- The baseline to target height ratio is a dominant factor.
- Maps of PDOP represent a very useful tool for showing the accuracy which can be obtained for a given radar constellation or for choosing the best node locations to cover a given surveillance area.

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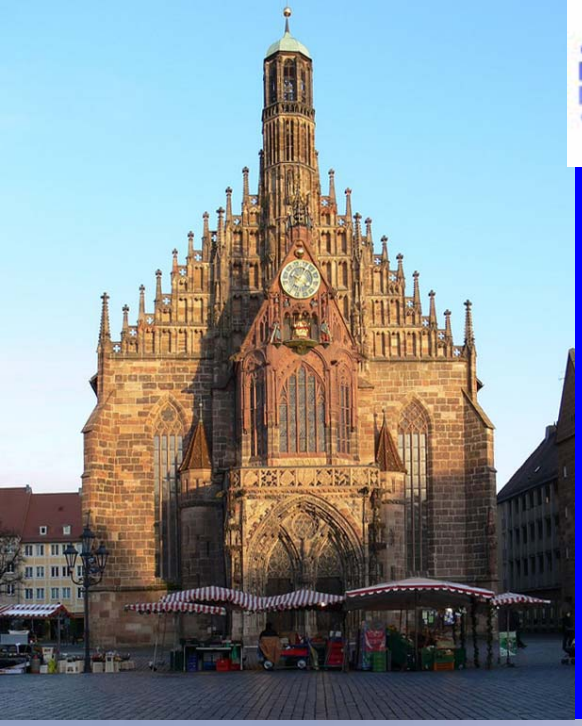

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- *Thank you!*

Q&A

Any questions?